

Initial Conditions and Global Event Properties

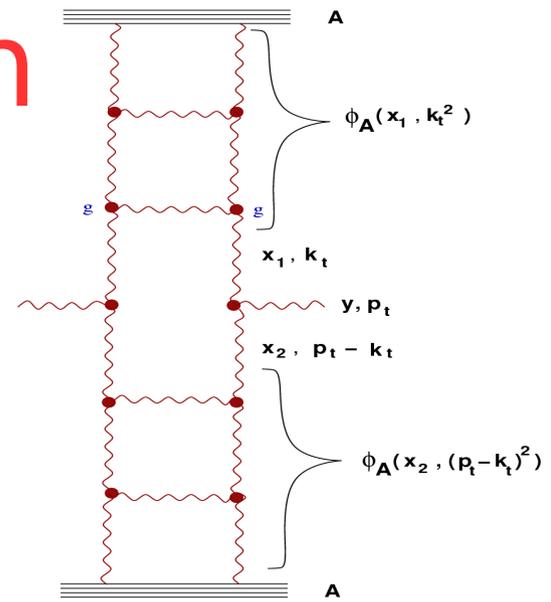
Adrian Dumitru

RIKEN-BNL and Baruch College/CUNY

- Initial conditions for hydro:
 - multiplicity
 - eccentricity
 - ecc. fluctuations
 - flux tubes and the ridge
- Ridge pure final-state effect or is it there in pp @ LHC ?

Inclusive gluon production

K_t -factorization:

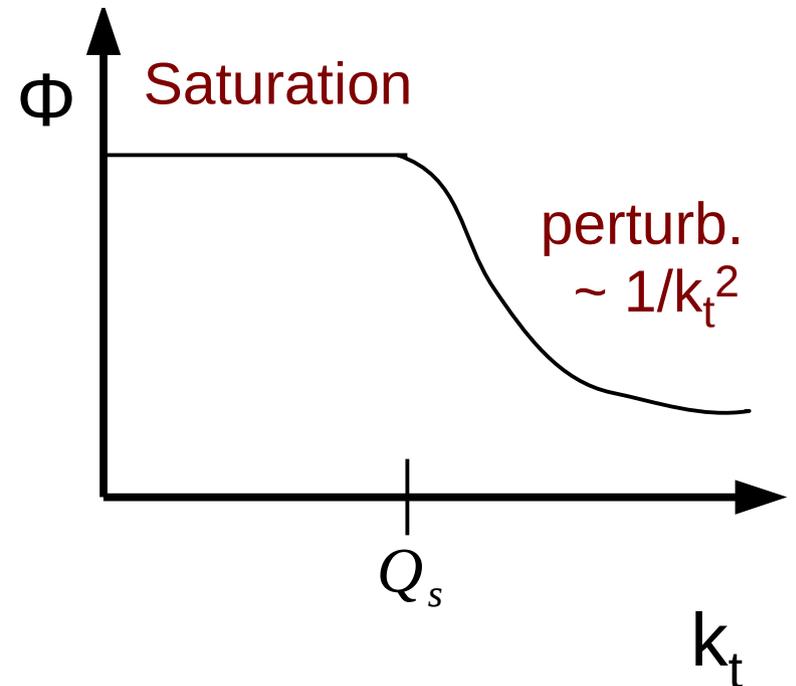


$$\frac{dN}{d^2r_t dy} \sim \int \frac{d^2p_t}{p_t^2} \int d^2k_t \alpha_s \phi_A(x_1, k_t^2) \phi_B(x_2, (p_t - k_t)^2)$$

Kharzeev, Levin, Nardi model:

$$\phi(x, k_t^2; \vec{r}_t) \sim \frac{1}{\alpha_s(Q_s^2)} \frac{Q_s^2(x, \vec{r}_t)}{\max(Q_s^2, k_T^2)}$$

$$Q_s^2 \sim \rho_{\text{part}} x^{-\lambda} \quad (\lambda \approx 0.28)$$

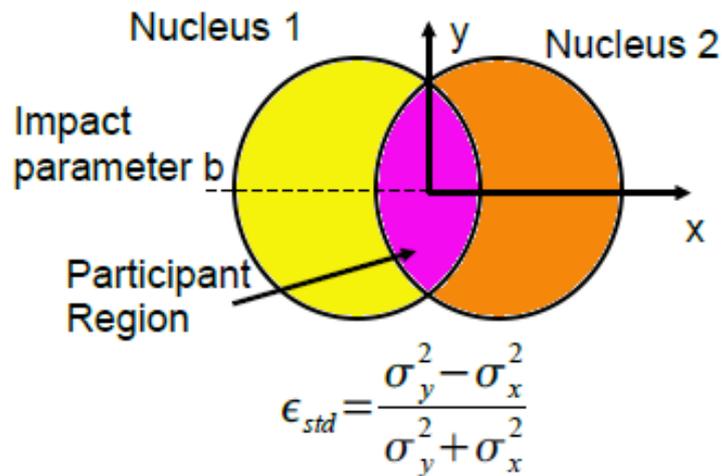


Fluctuations of nucleons (“light-cone sources”)

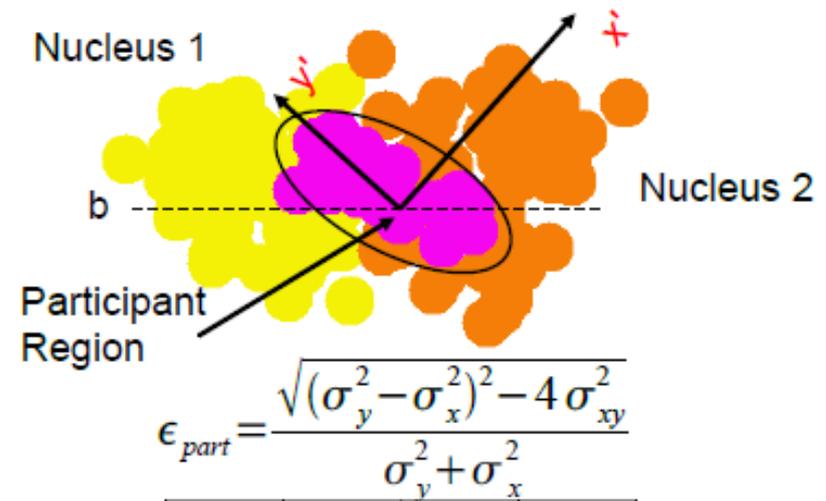
important for

- central / peripheral Au+Au
- smaller systems (Cu+Cu)
- fluctuations of v_2

Standard Eccentricity

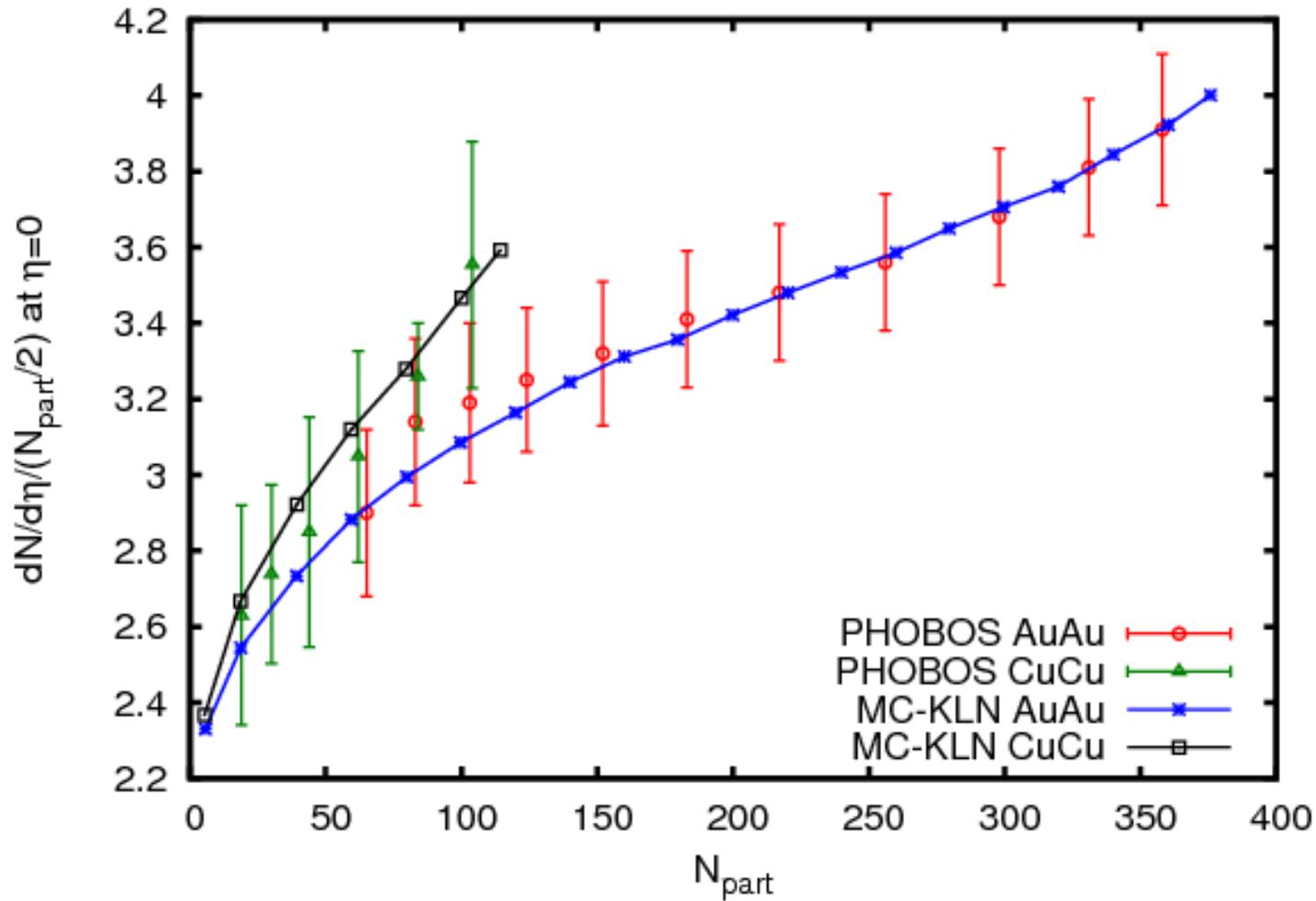


Participant Eccentricity



PHOBOS

Multiplicity \rightarrow

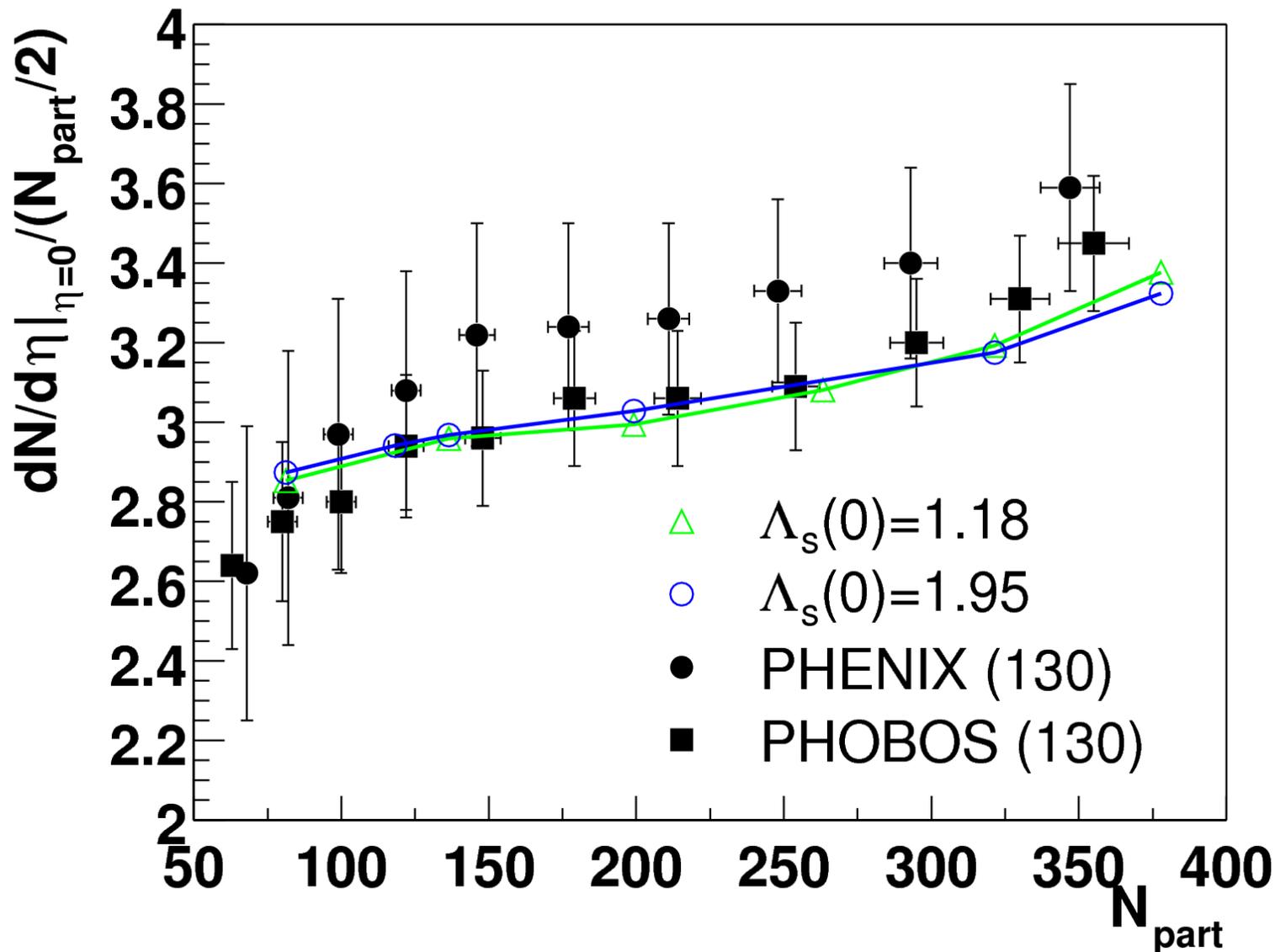


Centrality \rightarrow

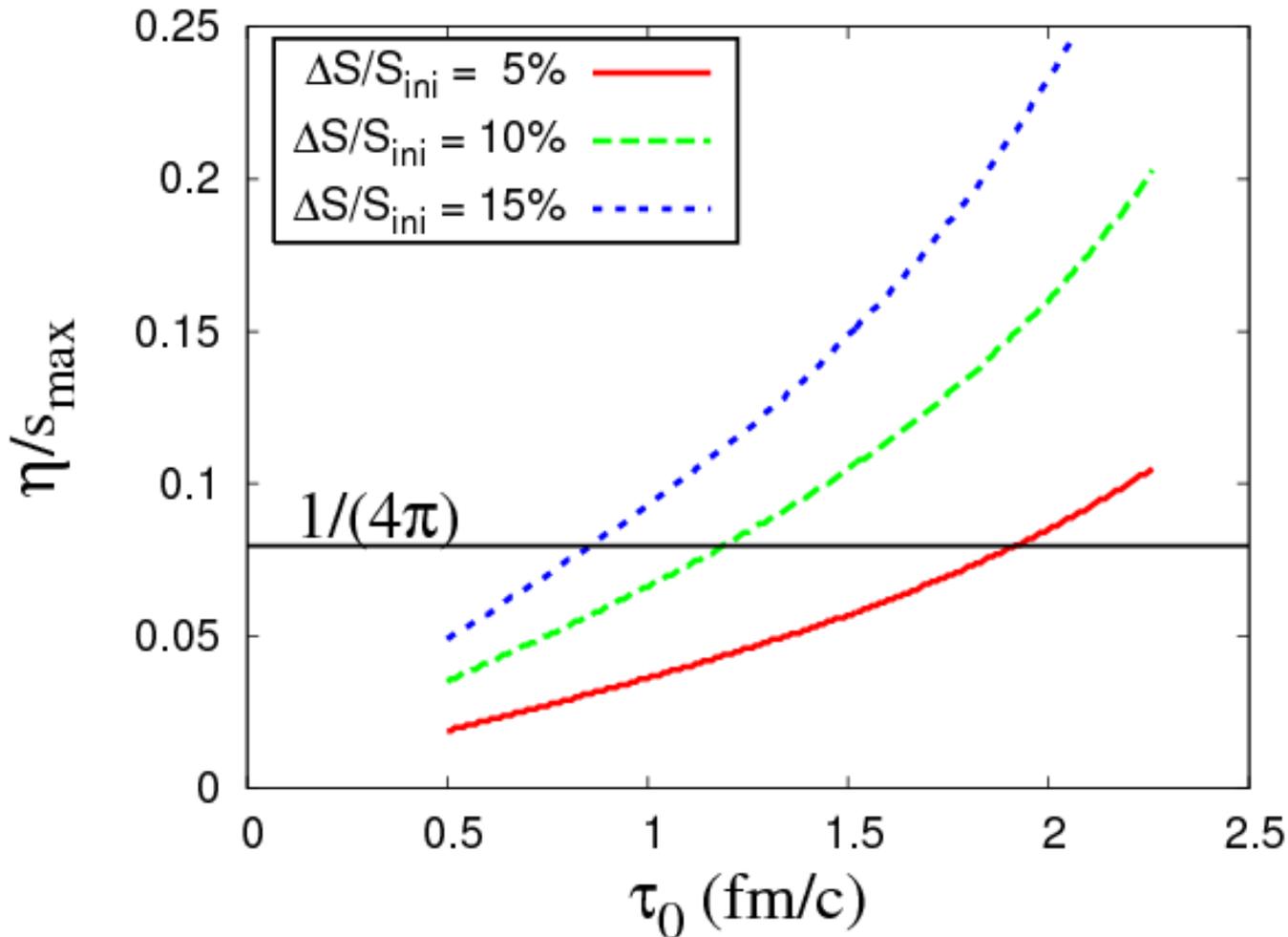
Very good fit, both Au+Au and Cu+Cu
pretty much down to pp
(too good, actually...)

Multiplicities in Au+Au from classical YM simulations / MV model

Krasnitz, Nara, Venugop.
hep-ph/0209269



$(\eta/s)_{\max}$ from entropy production bound

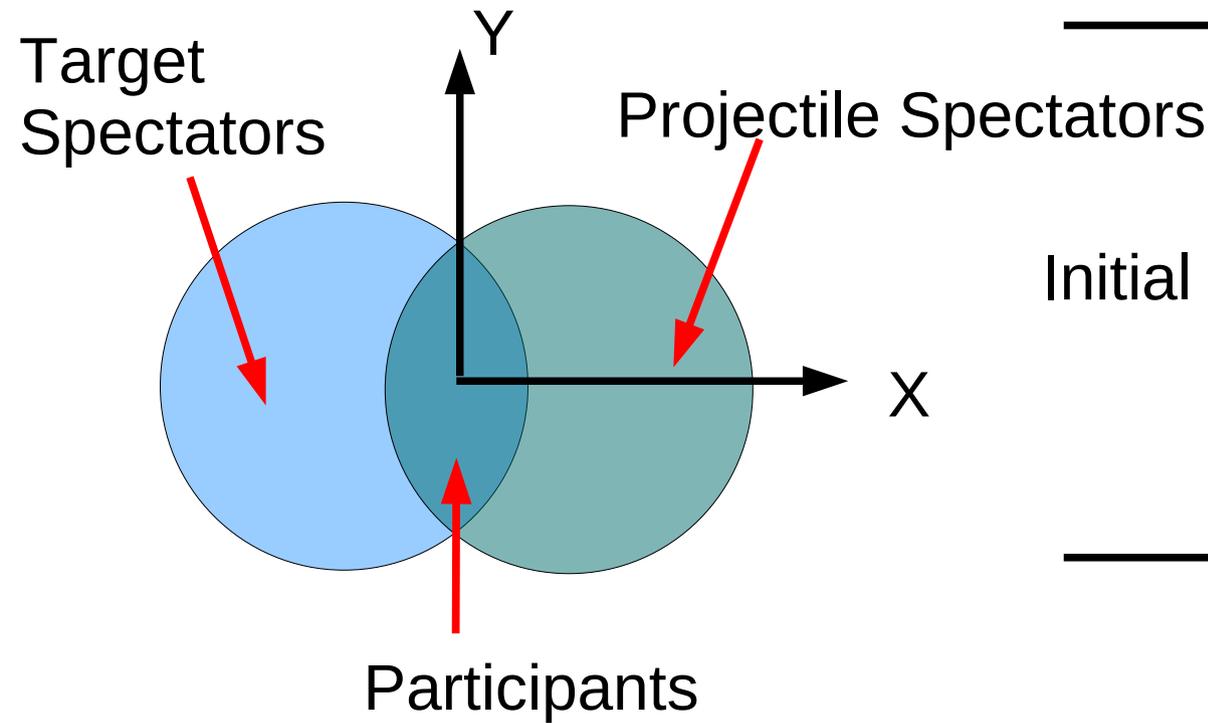


$$\delta T^{\mu\nu} = \eta \nabla u$$

A.D., E. Molnar, Y. Nara,
arXiv:0706.2203

- ◆ Correlates $(\eta/s)_{\max}$ with hydro initial time τ_0

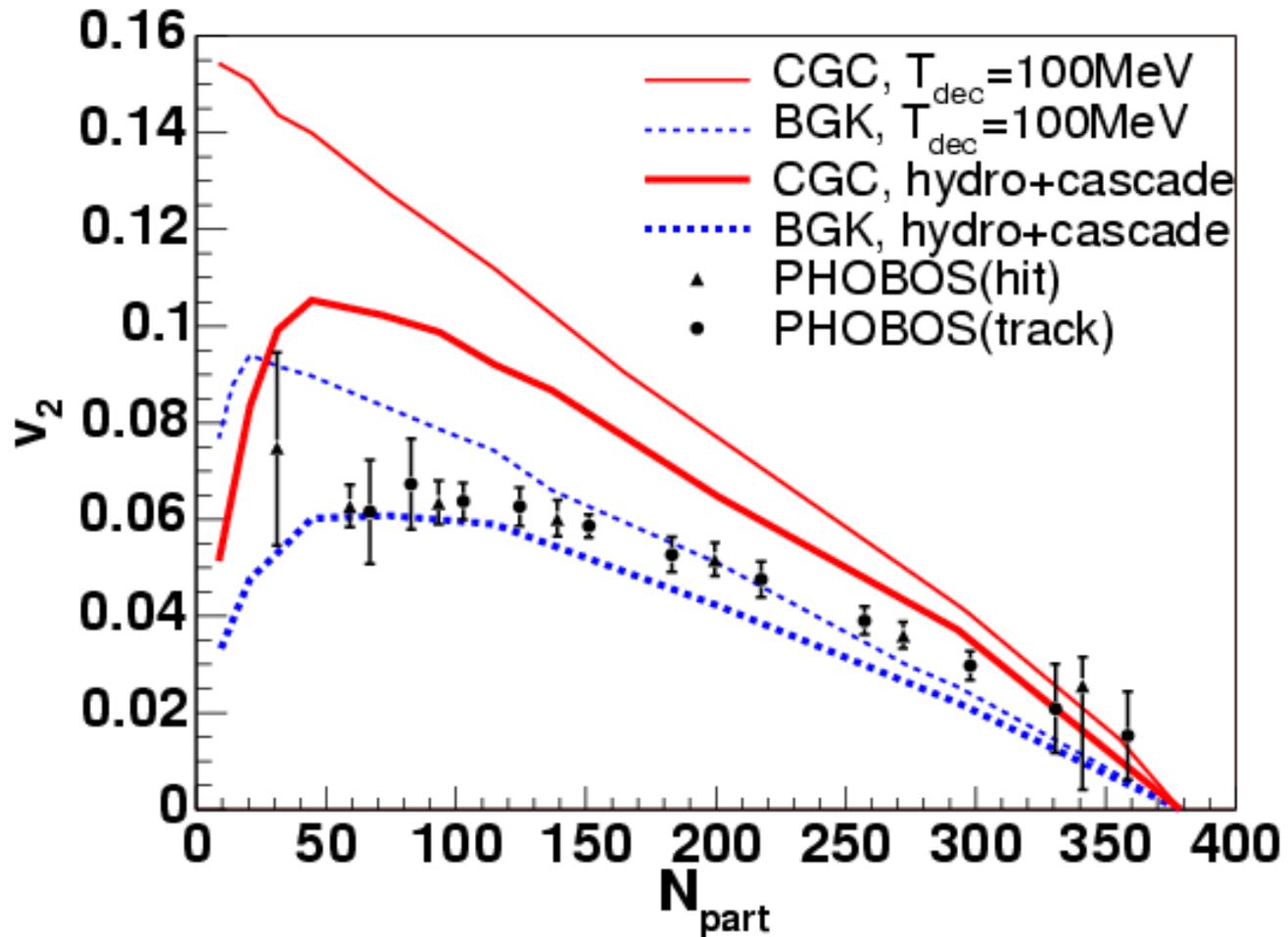
Pressure gradients and elliptic flow



	Coordinate space	Momentum space
	$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$	$v_2 = \frac{\langle p_x^r - p_y^r \rangle}{\langle p_x^r + p_y^r \rangle}$
Initial		
Later		

Idea : Pressure gradients convert spatial anisotropy to momentum anisotropy

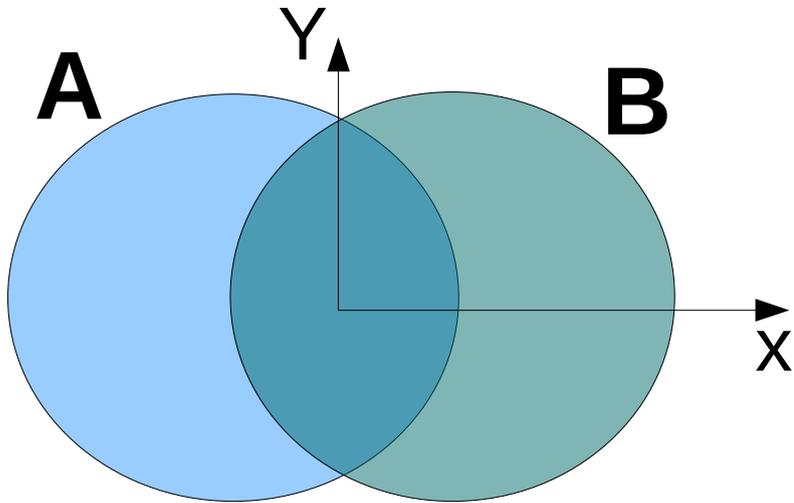
ideal Hydro with CGC vs. Glauber initial conditions



Transverse density:

nucl-th/0605012

$$\frac{dN_g}{d^2 r_\perp dy} = \frac{\Upsilon \pi N_c}{N_c^{\Upsilon-1}} \int \frac{d^2 p_t}{p_t^\Upsilon} \int d^2 k_t \alpha_s \phi(x_\perp, k_t^\Upsilon) \phi(x_\perp, (p_t - k_t)^\Upsilon)$$
$$\sim \underline{\underline{Q_{s\ min}^2}} \log \frac{Q_{s\ max}^2}{Q_{s\ min}^2}$$

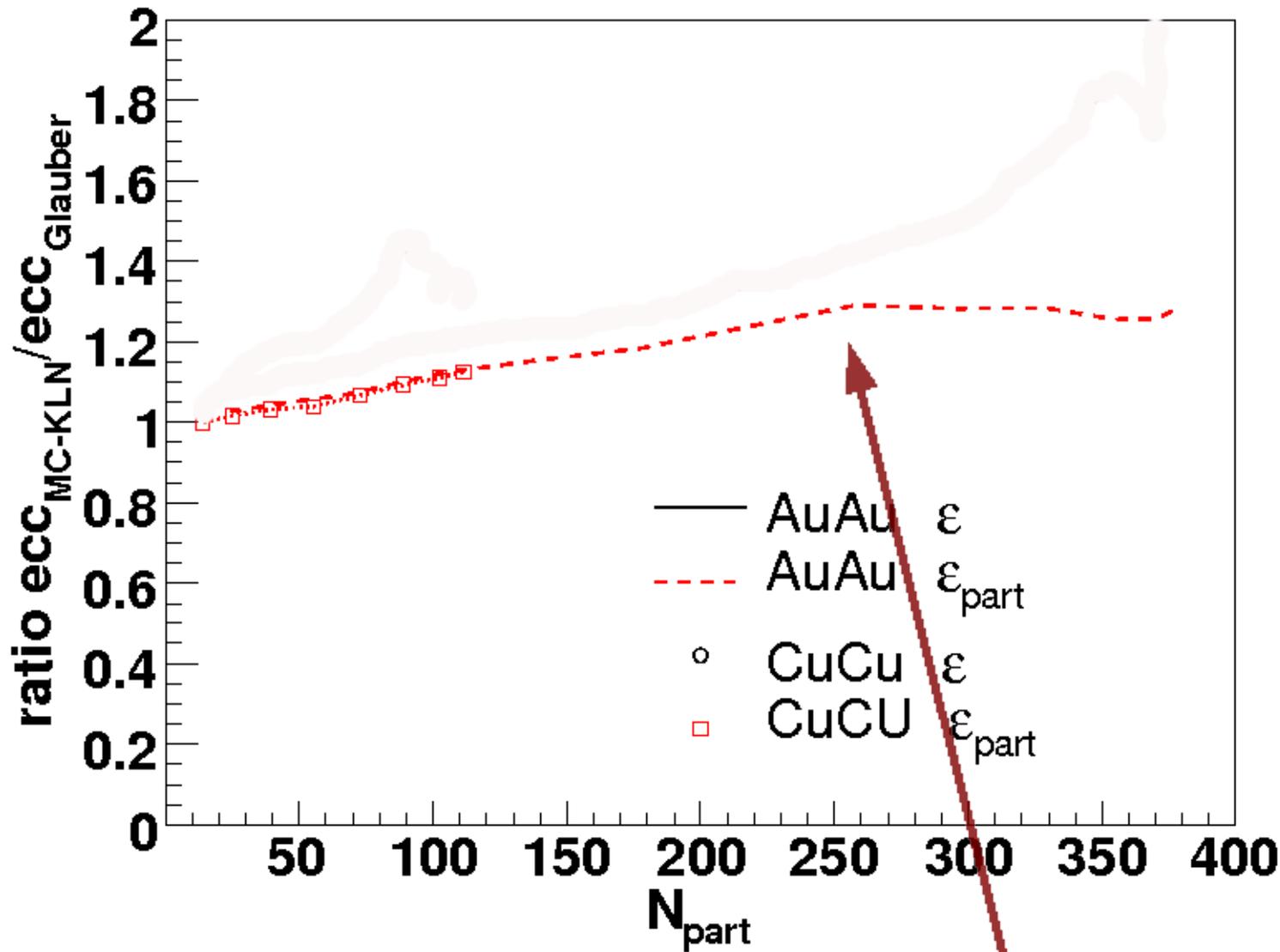


$$\text{CGC: } \frac{dN}{dy d^2 r} \sim \min(\rho_{\text{part}}^A, \rho_{\text{part}}^B)$$

$$\text{Glauber: } \frac{dN}{dy d^2 r} \sim \frac{\rho_{\text{part}}^A + \rho_{\text{part}}^B}{2}$$



$$\epsilon_{CGC} > \epsilon_{Glauber}$$

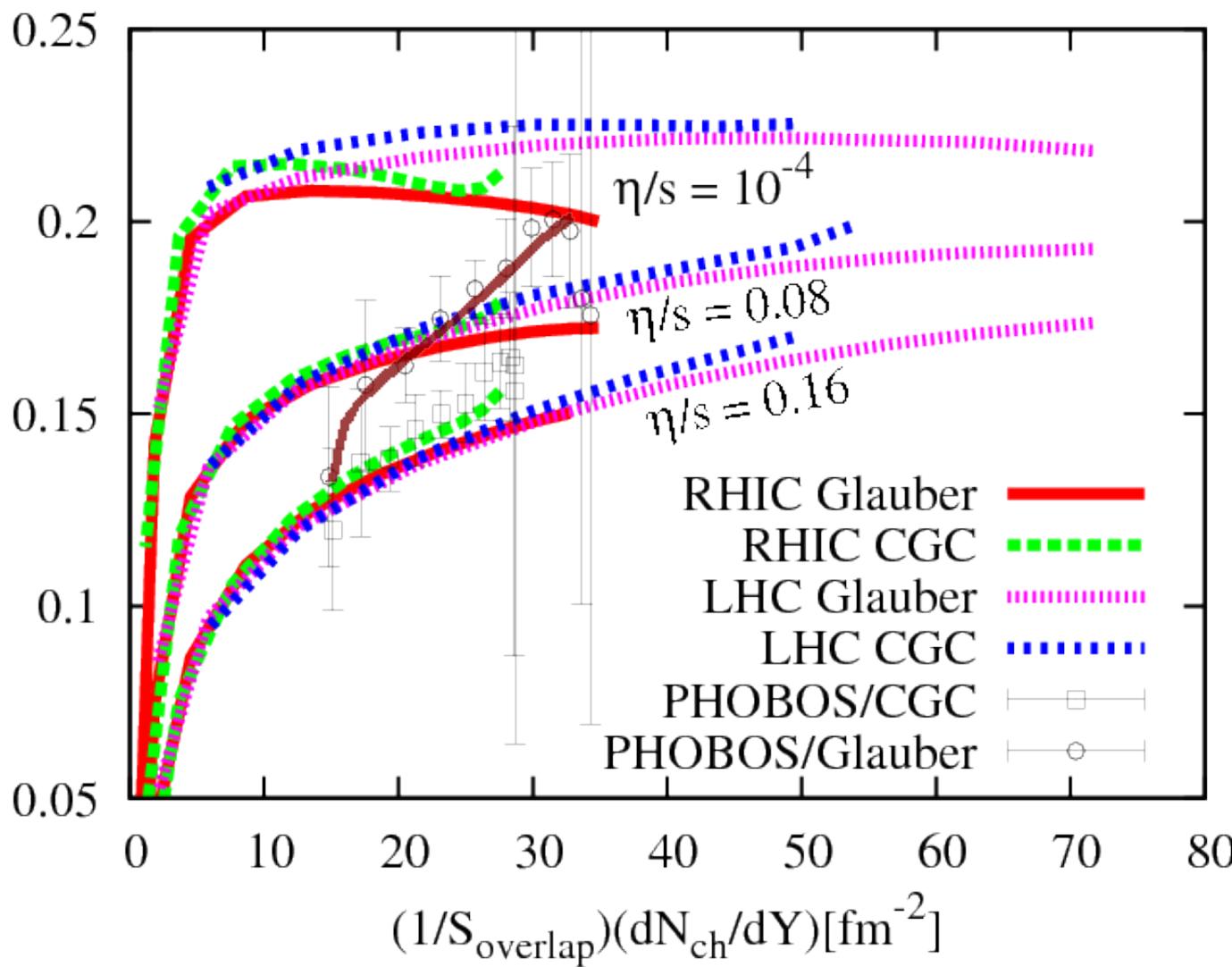


~ 25-30% effect, comparable to
dissip. correction

should be flat
in conformal
limit !

broken by λ/R ,
 T_{fo}/T_i , T_c/T_i , ...

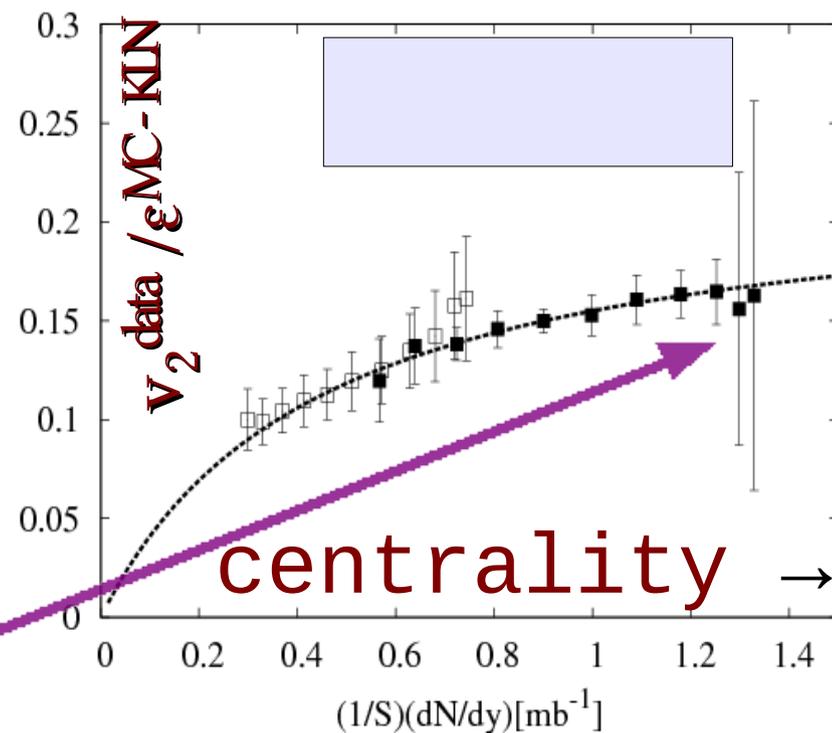
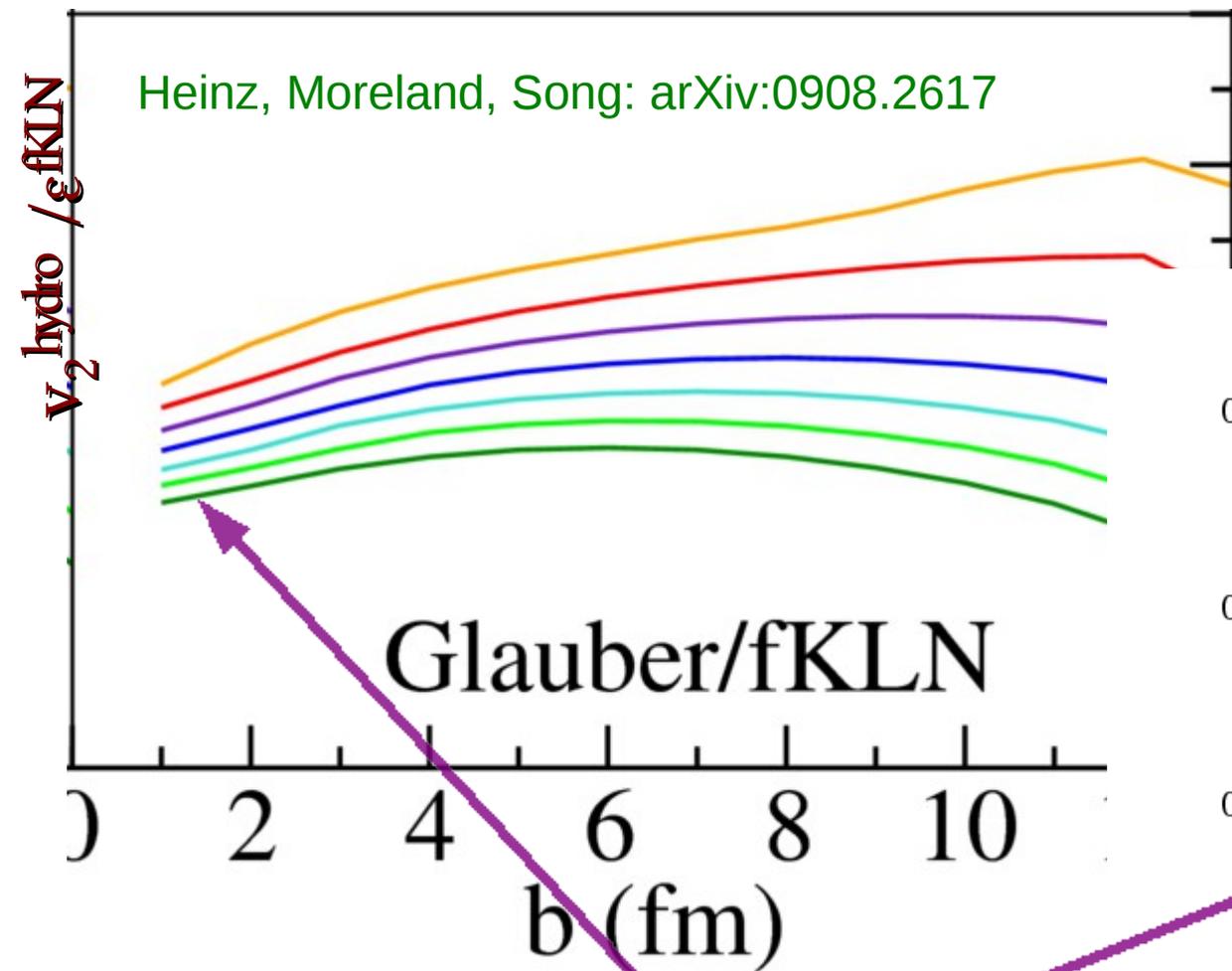
$0.5 e_p/e_x (\approx v_2/e_x)$



rather steep (non-hydro like) v_2/ϵ for Glauber I.C.

→ hydro + Glauber ain't good friends !?

scaled flow vs density



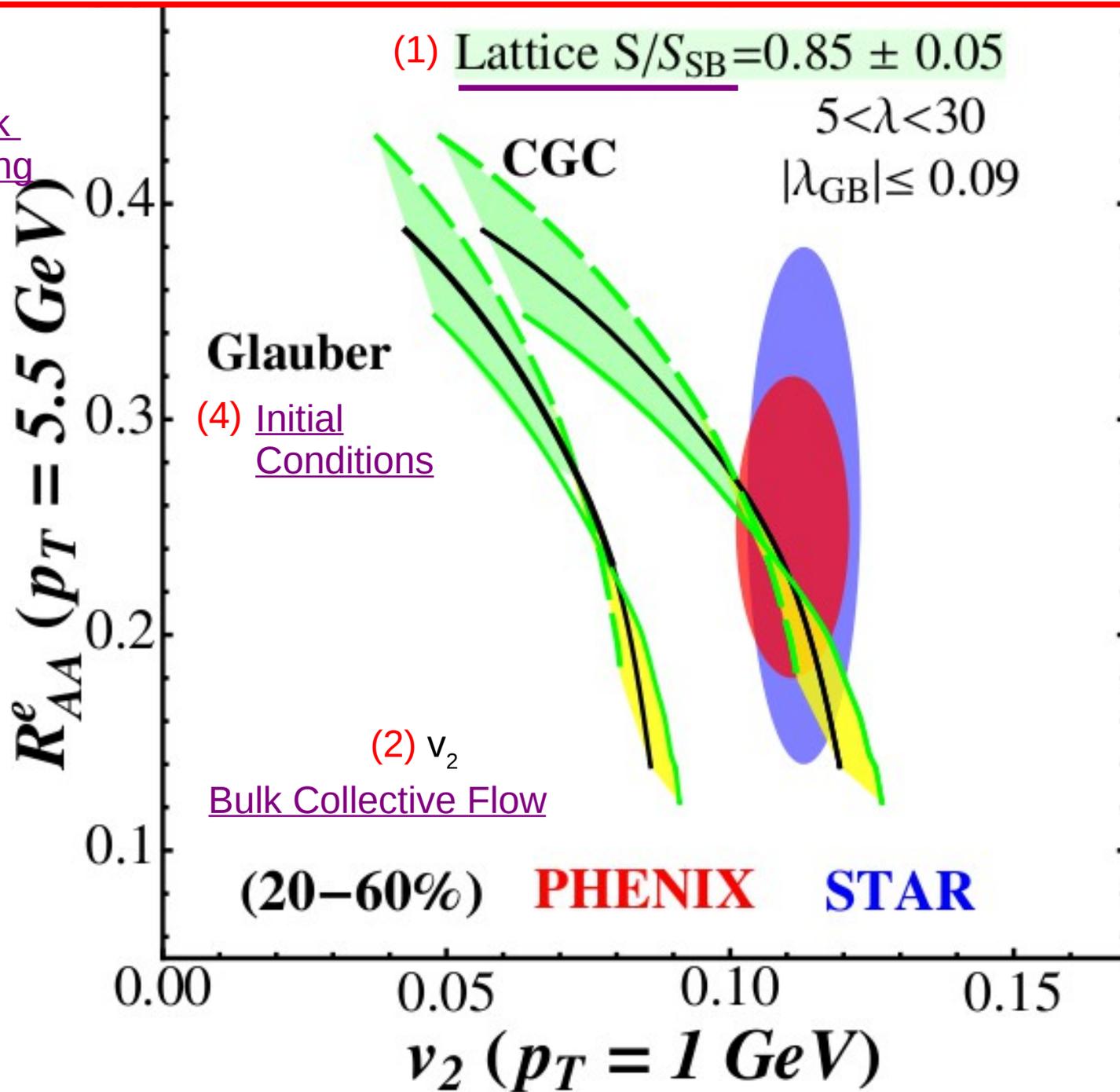
$v_2^{\text{data}} / \epsilon^{\text{MC-KLN}}$ increases with centrality!

(unlike Glauber-hydro)

at small b , one should account for fluctuations though.

AdS Holography: Test of Consistency of **Soft + Hard** observables

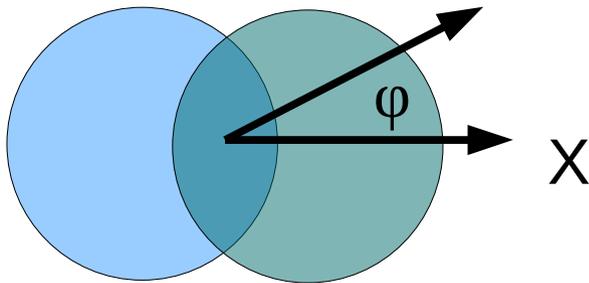
(3) RAAe
Heavy quark
Jet quenching



dE/dx
vs
 η/s

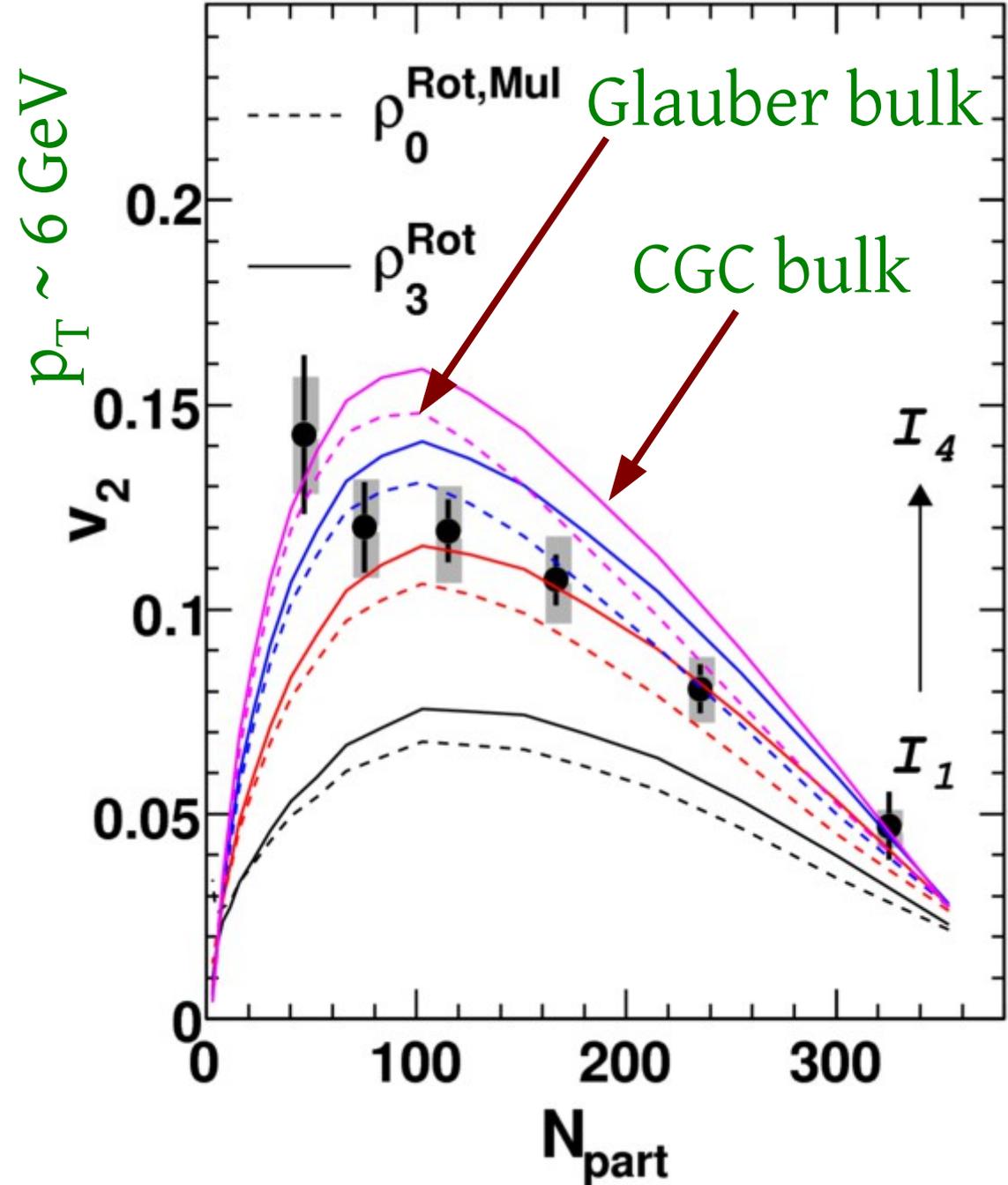
The Future

v_2 of jets:



Survival probability:

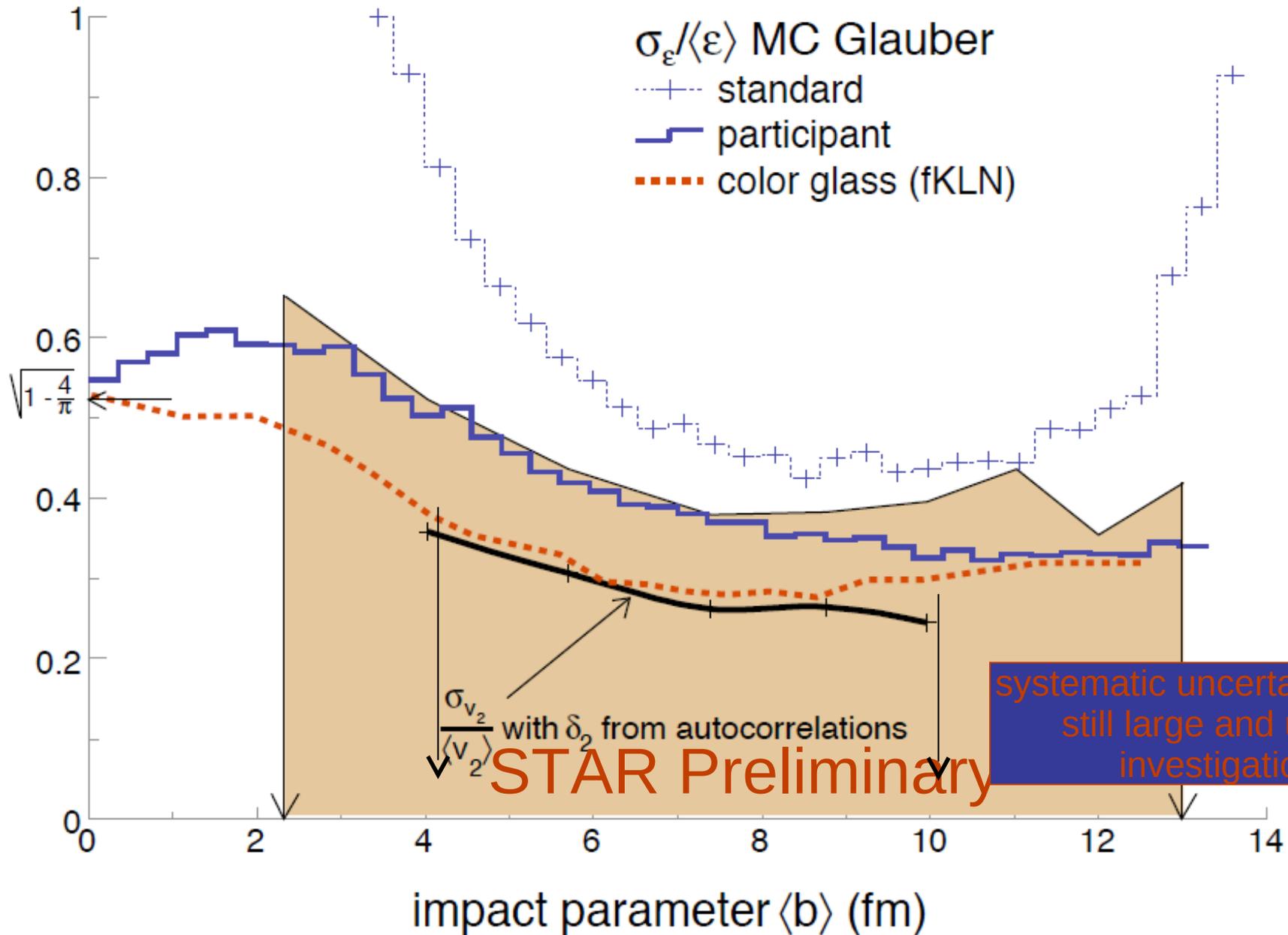
$$f = \exp[-\kappa I(\phi)]$$



comparison to geometric σ_ϵ

fluctuations from finite bin widths have not been removed yet
likely to reduce ratio below the model!

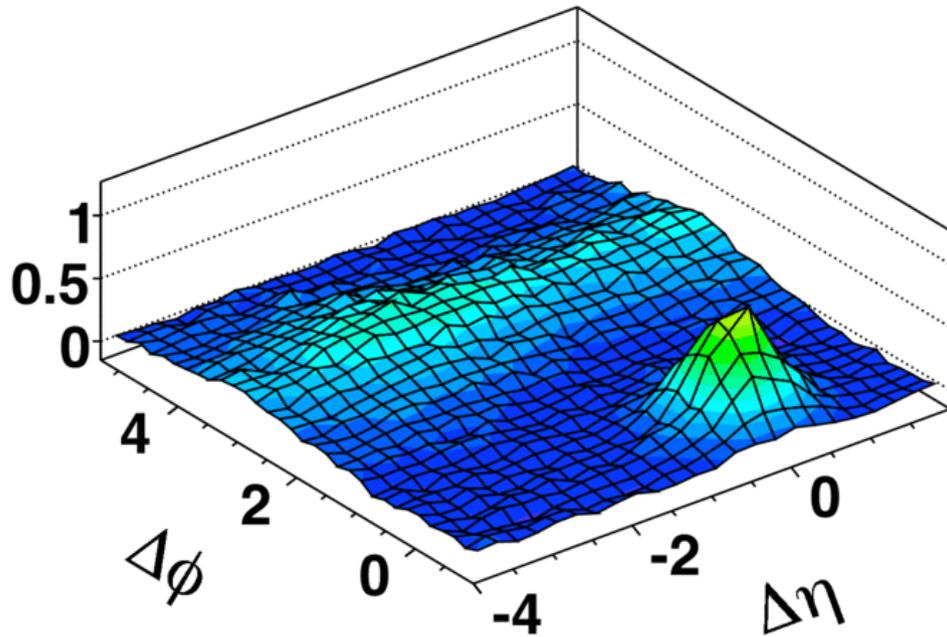
$$\frac{\sigma_{v_2}}{\langle v_2 \rangle}$$



P. Sorensen @ "Early Time Dynamics",
McGill, July 2007

exciting discovery by STAR:

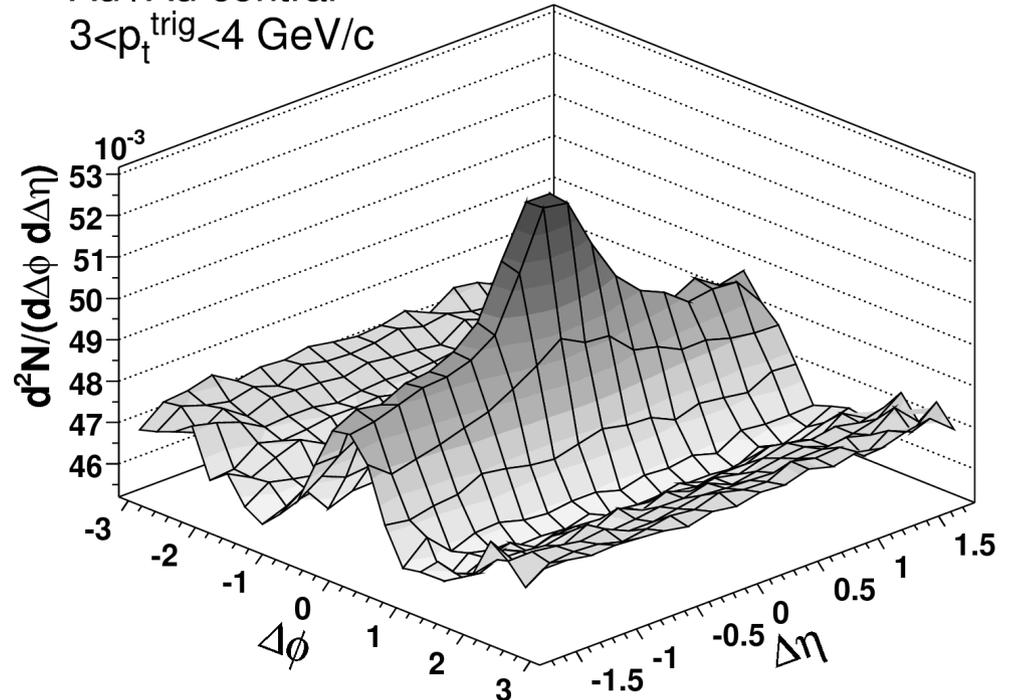
long-range rapidity
correlations at RHIC !



PYTHIA pp, $p_T^{\text{trig}} > 2.5 \text{ GeV}$

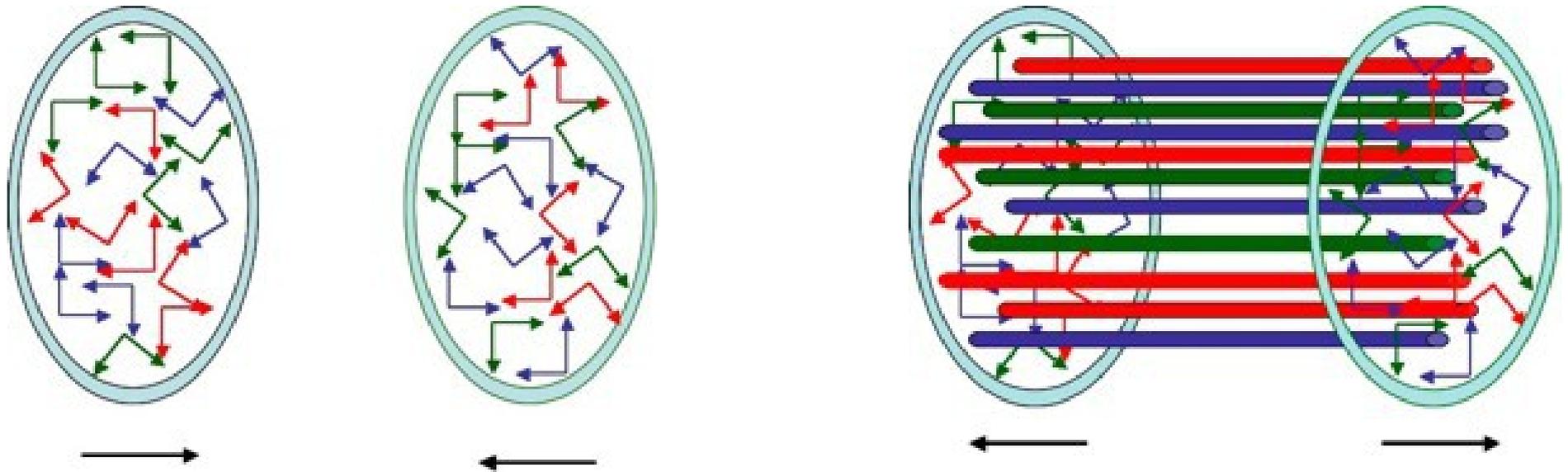
STAR (arXiv:0909.0191)

Au+Au central
 $3 < p_T^{\text{trig}} < 4 \text{ GeV}/c$



Glasma flux tubes

Lappi + McLerran NPA 2006



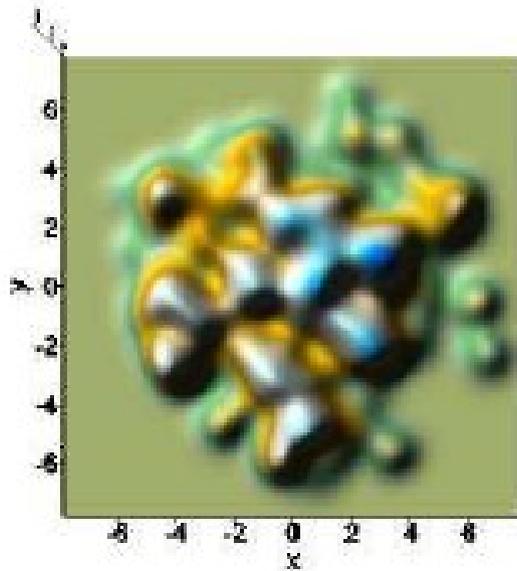
before collision

right after impact

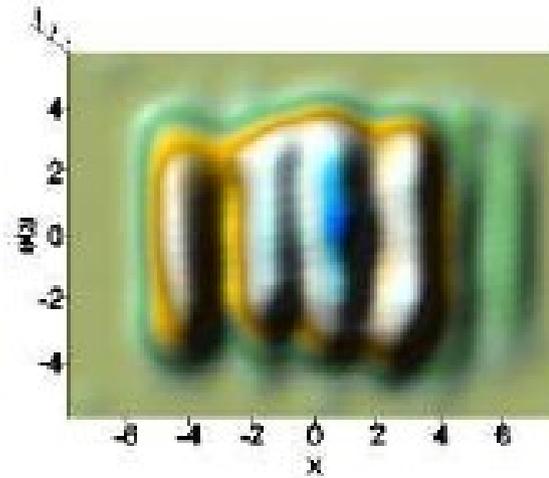
$$E^z = ig [A_1^i, A_2^i] \quad , \quad B^z = ig \epsilon^{ij} [A_1^i, A_2^j]$$

propagation of “topological structures” :

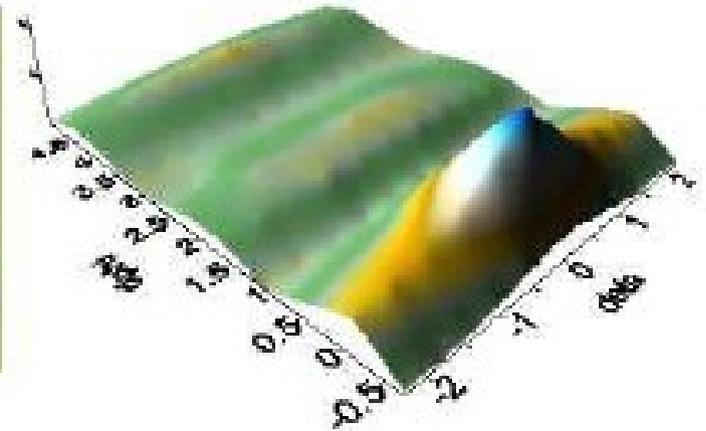
J. Takahashi et al, PRL 2009
E. Shuryak, PRC 2009



$\eta = 0$



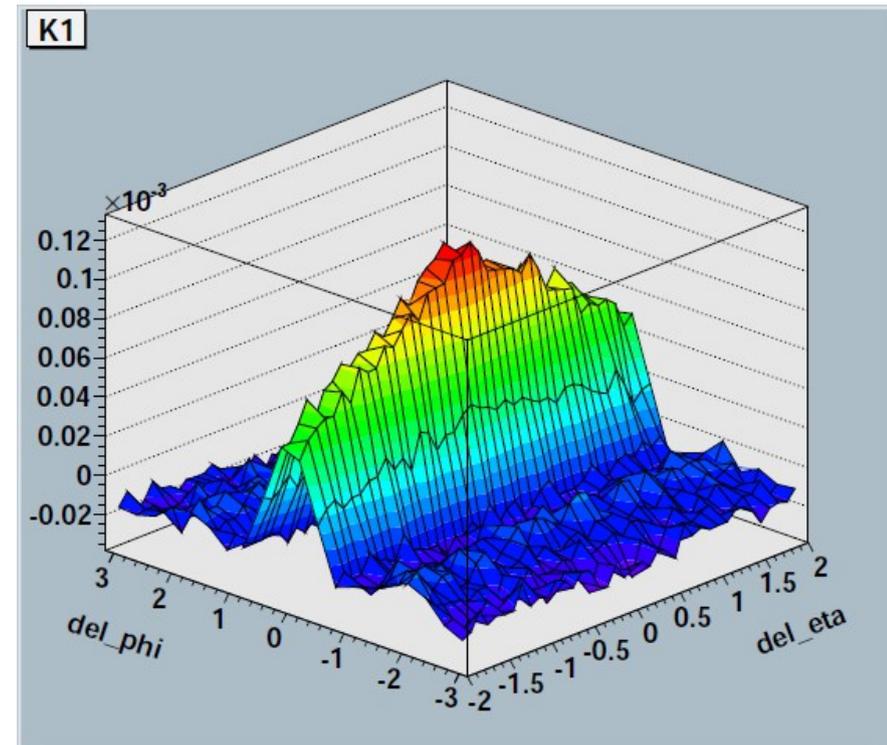
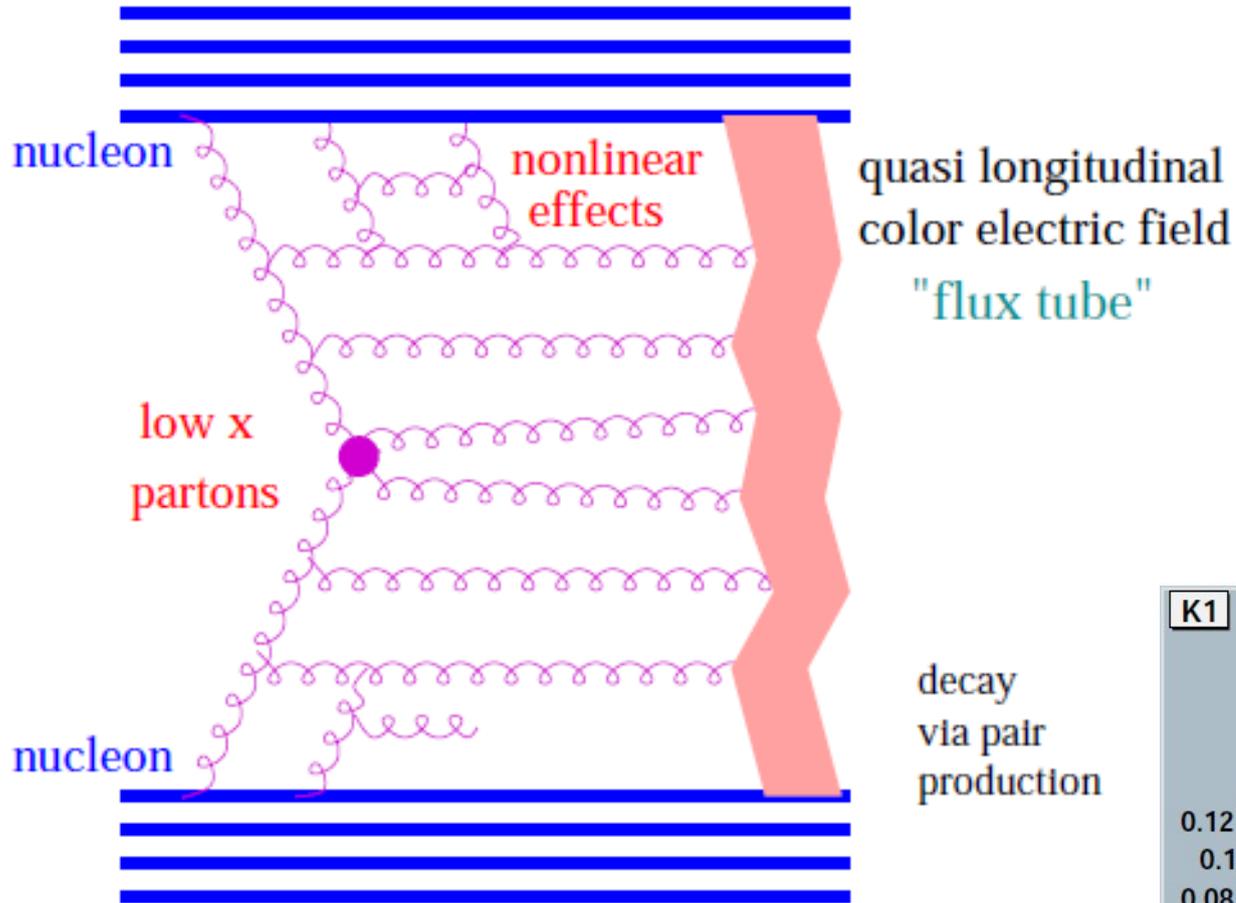
$y = 0$



R. Andrade, arXiv:0912.0703

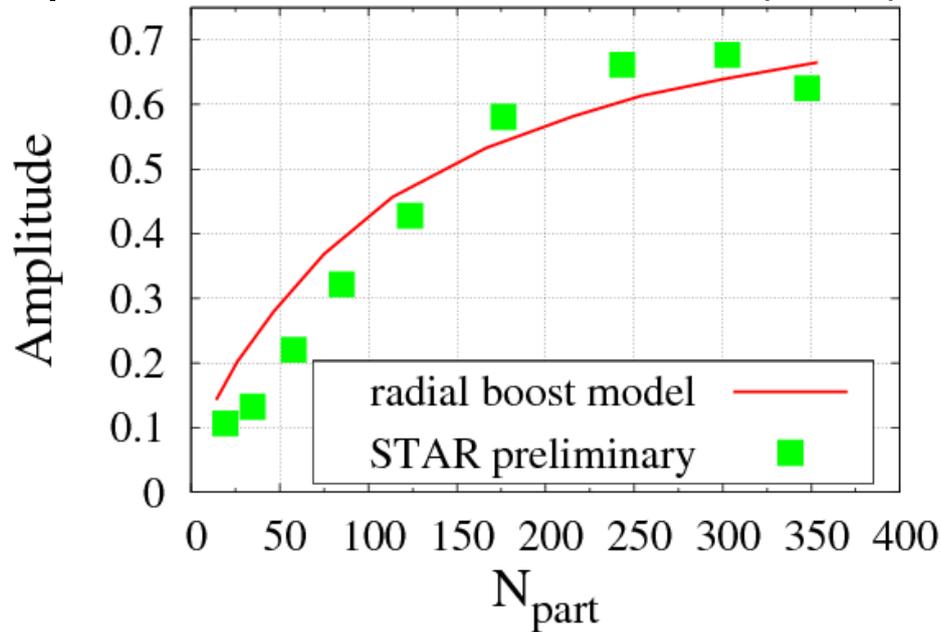
EPOS string model

K. Werner et al,
arXiv:1004.0805



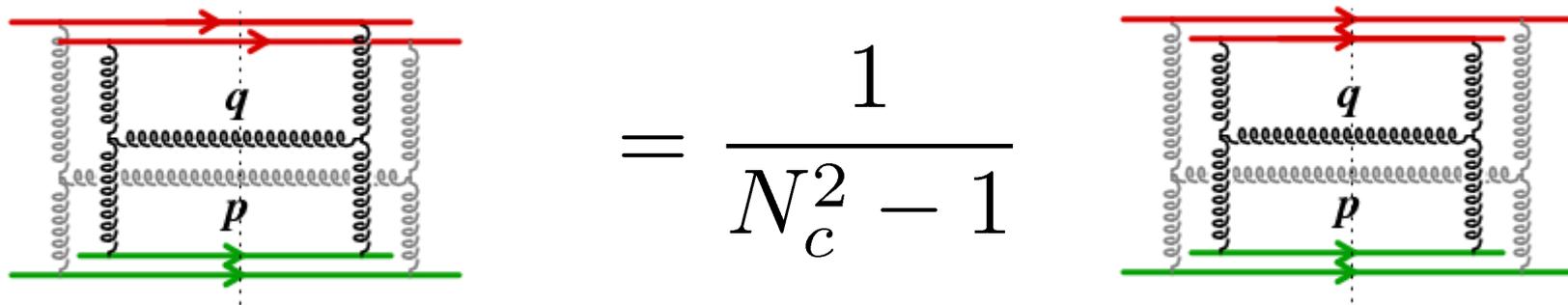
Amplitude after radial boost (flow):

$$\mathcal{A} = K_R \frac{\gamma_B - \gamma_B^{-1}}{\alpha_s(Q_s)}$$

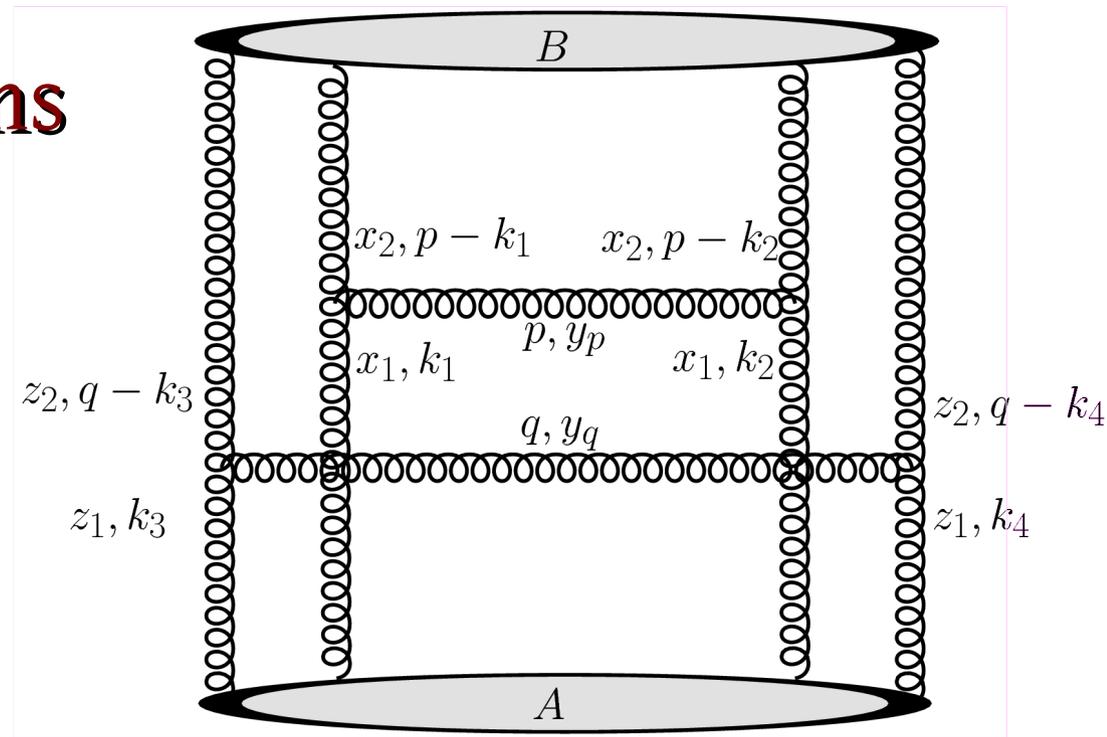


A.D., Gelis, McLerran,
Venugopalan: 0804.3858

However, two-particle production diagrams are N_c -suppressed:



**genuine B-JIMWLK terms
from THIS diagram:**



B-JIMWLK four-point function (in Gaussian approximation), incl. “Nc corrections”:

$$\langle \rho^a \rho^b \rho^c \rho^d \rangle = \delta^{ab} \delta^{cd} \langle \rho^2 \rangle^2 + \frac{1}{N_c} f^{abe} f^{cde} \mathcal{F}(k_i) \langle \rho^2 \rangle^2 + \dots$$

A.D., J. Jalilian-Marian,
arXiv:1001.4820

★ ridge in pp @ LHC ?!

Summary

- non-trivial QCD dynamics determines initial conditions for hydro:
 - ◆ η/s versus τ_0
 - ◆ v_2/ε versus centrality (deviation from conform.)
 - ◆ R_{AA}^Q , v_2^{jet}
- initial state also seen via “topological structures” / flux tubes / long-range correl. which survive hydro evolution
 - ◆ confirmation from pp @ LHC would improve our understanding

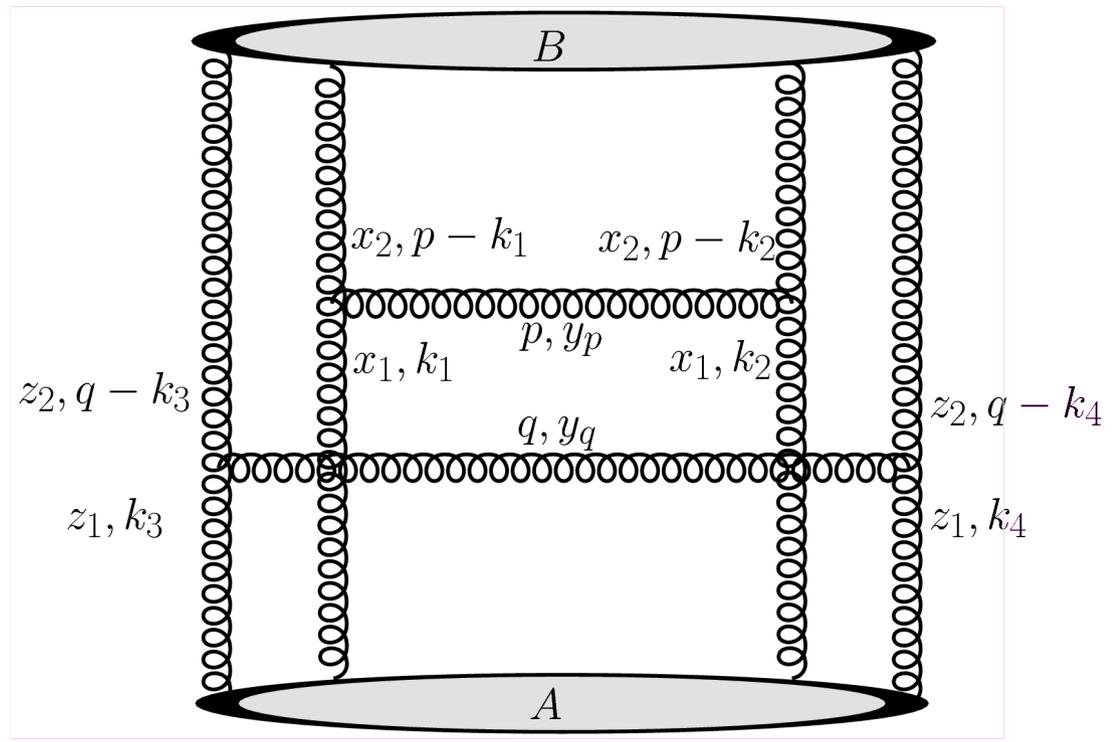
BACKUP SLIDES

R_{AA}^e can test AdS gravity dual models via

$$R_{\text{AA}}^Q(p_T, b) = \int_0^{2\pi} d\phi \int d^2\vec{x}_\perp \frac{T_{\text{AA}}(\vec{x}_\perp, b)}{2\pi N_{\text{bin}}(b)} \times \exp[-n_Q(p_T)F_Q(\vec{x}_\perp, \phi)] \quad (14)$$

where N_{Bin} is the number of binary collisions and

$$F_Q(\vec{x}_\perp, \phi) = \sqrt{\lambda} \frac{\pi}{2M_Q} \left(1 + \frac{3}{2} \lambda_{\text{GB}} + \frac{15}{16} \frac{\zeta(3)}{\lambda^{3/2}} \right) \times \int_{\tau_0}^{\infty} d\tau T^2(\vec{l}, \tau) \theta(T(\vec{l}, \tau) - T_f). \quad (15)$$



$$\begin{aligned}
C(p_{\perp}, q_{\perp}) = & \frac{g^{12}}{64(2\pi)^6} (f_{abc} f_{a'\bar{b}\bar{c}} f_{a\hat{b}\hat{c}} f_{a'\tilde{b}\tilde{c}}) \int \prod_{i=1}^4 \frac{d^2 k_{i\perp}}{(2\pi)^2 k_{i\perp}^2} \\
& \times \frac{L_{\mu}(p_{\perp}, k_{1\perp}) L^{\mu}(p_{\perp}, k_{2\perp}) L_{\nu}(q_{\perp}, k_{3\perp}) L^{\nu}(q_{\perp}, k_{4\perp})}{(p_{\perp} - k_{1\perp})^2 (p_{\perp} - k_{2\perp})^2 (q_{\perp} - k_{3\perp})^2 (q_{\perp} - k_{4\perp})^2} \\
& \times \left\langle \rho_1^{*\hat{b}}(k_{2\perp}) \rho_1^{*\tilde{b}}(k_{4\perp}) \rho_1^b(k_{1\perp}) \rho_1^{\bar{b}}(k_{3\perp}) \right\rangle \\
& \times \left\langle \rho_2^{*\hat{c}}(p_{\perp} - k_{2\perp}) \rho_2^{*\tilde{c}}(q_{\perp} - k_{4\perp}) \rho_2^c(p_{\perp} - k_{1\perp}) \rho_2^{\bar{c}}(q_{\perp} - k_{3\perp}) \right\rangle
\end{aligned}$$

Complete B-JIMWLK four-point function: (no Gaussian approx.)

$$\begin{aligned}
\frac{d}{dY} \langle \alpha_r^a \alpha_{\bar{r}}^b \alpha_s^c \alpha_{\bar{s}}^d \rangle = & \\
& \frac{g^2 N_c}{(2\pi)^3} \int d^2 z \left\langle \frac{\alpha_z^a \alpha_{\bar{r}}^b \alpha_s^c \alpha_{\bar{s}}^d}{(r-z)^2} + \frac{\alpha_r^a \alpha_z^b \alpha_s^c \alpha_{\bar{s}}^d}{(\bar{r}-z)^2} + \frac{\alpha_r^a \alpha_{\bar{r}}^b \alpha_z^c \alpha_{\bar{s}}^d}{(s-z)^2} + \frac{\alpha_r^a \alpha_{\bar{r}}^b \alpha_s^c \alpha_z^d}{(\bar{s}-z)^2} - 4 \frac{\alpha_r^a \alpha_{\bar{r}}^b \alpha_s^c \alpha_{\bar{s}}^d}{z^2} \right\rangle \\
& + \frac{g^2}{\pi} \int \frac{d^2 z}{(2\pi)^2} \left\langle f^{\epsilon\kappa a} f^{f\kappa b} \frac{(r-z) \cdot (\bar{r}-z)}{(r-z)^2 (\bar{r}-z)^2} \left[\alpha_r^e \alpha_{\bar{r}}^f - \alpha_r^e \alpha_z^f - \alpha_z^e \alpha_{\bar{r}}^f + \alpha_z^e \alpha_z^f \right] \alpha_s^c \alpha_{\bar{s}}^d \right. \\
& \quad + f^{\epsilon\kappa a} f^{f\kappa c} \frac{(r-z) \cdot (s-z)}{(r-z)^2 (s-z)^2} \left[\alpha_r^e \alpha_s^f - \alpha_r^e \alpha_z^f - \alpha_z^e \alpha_s^f + \alpha_z^e \alpha_z^f \right] \alpha_{\bar{r}}^b \alpha_{\bar{s}}^d \\
& \quad + f^{\epsilon\kappa a} f^{f\kappa d} \frac{(r-z) \cdot (\bar{s}-z)}{(r-z)^2 (\bar{s}-z)^2} \left[\alpha_r^e \alpha_{\bar{s}}^f - \alpha_r^e \alpha_z^f - \alpha_z^e \alpha_{\bar{s}}^f + \alpha_z^e \alpha_z^f \right] \alpha_{\bar{r}}^b \alpha_s^c \\
& \quad + f^{\epsilon\kappa b} f^{f\kappa c} \frac{(\bar{r}-z) \cdot (s-z)}{(\bar{r}-z)^2 (s-z)^2} \left[\alpha_{\bar{r}}^e \alpha_s^f - \alpha_{\bar{r}}^e \alpha_z^f - \alpha_z^e \alpha_s^f + \alpha_z^e \alpha_z^f \right] \alpha_r^a \alpha_{\bar{s}}^d \\
& \quad + f^{\epsilon\kappa b} f^{f\kappa d} \frac{(\bar{r}-z) \cdot (\bar{s}-z)}{(\bar{r}-z)^2 (\bar{s}-z)^2} \left[\alpha_{\bar{r}}^e \alpha_{\bar{s}}^f - \alpha_{\bar{r}}^e \alpha_z^f - \alpha_z^e \alpha_{\bar{s}}^f + \alpha_z^e \alpha_z^f \right] \alpha_r^a \alpha_s^c \\
& \quad \left. + f^{\epsilon\kappa c} f^{f\kappa d} \frac{(s-z) \cdot (\bar{s}-z)}{(s-z)^2 (\bar{s}-z)^2} \left[\alpha_s^e \alpha_{\bar{s}}^f - \alpha_s^e \alpha_z^f - \alpha_z^e \alpha_{\bar{s}}^f + \alpha_z^e \alpha_z^f \right] \alpha_r^a \alpha_{\bar{r}}^b \right\rangle .
\end{aligned}$$

$$A^\mu(x^+, r) \equiv \delta^{\mu-} \alpha(x^+, r) = -g \delta^{\mu-} \delta(x^+) \frac{1}{\nabla_\perp^2} \rho(x^+, r) \quad k^2 \alpha(k) = g \rho(k)$$

however, “subleading- N_c ” piece
contributes at the same order to $C(p,q)$

Complete Balitsky/JIMWLK four-point function:
(in Gaussian approximation)

$$\langle \rho^a \rho^b \rho^c \rho^d \rangle = \delta^{ab} \delta^{cd} \langle \rho^2 \rangle^2 + \frac{1}{N_c} f^{ab\kappa} f^{cd\kappa} \langle \rho^2 \rangle^2 + \dots$$

$$f_{gaa'} f_{g'bb'} f_{gcc'} f_{g'dd'} \delta^{ac} \delta^{bd} \delta^{a'b'} \delta^{c'd'} = N_c^2 (N_c^2 - 1)$$

$$f_{gaa'} f_{g'bb'} f_{gcc'} f_{g'dd'} \frac{1}{N_c} f^{ab\kappa} f^{cd\kappa} \delta^{a'c'} \delta^{b'd'} = N_c^2 (N_c^2 - 1)$$

Projectile Target

[Note: independent/uncorrel. production

$$f_{gaa'} f_{g'bb'} f_{gcc'} f_{g'dd'} \delta^{ac} \delta^{bd} \delta^{a'c'} \delta^{b'd'} = N_c^2 (N_c^2 - 1)^2$$

]